arXiv:1209.0282v1 [hep-ex] 3 Sep 2012

Measurement of the fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The LHCb collaboration[†]

Abstract

The production of $\chi_b(1P)$ mesons in pp collisions at a centre-of-mass energy of 7 TeV is studied using $32\,\text{pb}^{-1}$ of data collected with the LHCb detector. The $\chi_b(1P)$ mesons are reconstructed in the decay mode $\chi_b(1P) \to \Upsilon(1S)\gamma \to \mu^+\mu^-\gamma$. The fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays in the $\Upsilon(1S)$ transverse momentum range $6 < p_{\text{T}}^{\Upsilon(1S)} < 15\,\text{GeV}/c$ and rapidity range $2.0 < y^{\Upsilon(1S)} < 4.5$ is measured to be $(20.7 \pm 5.7 \pm 2.1^{+2.7}_{-5.4})\%$, where the first uncertainty is statistical, the second is systematic and the last gives the range of the result due to the unknown $\Upsilon(1S)$ and $\chi_b(1P)$ polarizations.

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1   Introduction

The production of heavy quarkonium states at hadron colliders is a subject of experimental and theoretical interest [1]. The non-relativistic QCD (NRQCD) factorization approach has been developed to describe the inclusive production and decay of quarkonia [2]. The LHCb experiment has measured the production of inclusive $J/\psi \to \mu^+\mu^-$ [3], $\psi(2S)$ [4] and $\Upsilon(nS) \to \mu^+\mu^-$ ($n = 1, 2, 3$) [5] mesons in pp collisions as a function of the quarkonium transverse momentum p_{T} and rapidity y over the range $0 < p_{\mathrm{T}} < 15\,\mathrm{GeV}/c$ and $2.0 < y < 4.5$. A significant fraction of the cross-section for both J/ψ and $\Upsilon(nS)$ production is expected to be due to feed-down from higher quarkonium states. Understanding the size of this effect is important for the interpretation of the quarkonia cross-section and polarization data. A few experimental studies of hadroproduction of P-wave quarkonia have been reported. In the case of the χ_{cJ} states, with spin $J = 0, 1, 2$, measurements from the CDF [6, 7], HERA-B [8] and LHCb [9, 10] experiments exist, while χ_{bJ} related measurements have been reported by the CDF [11], ATLAS [12] and D0 [13] experiments.

This paper reports studies of the inclusive production of the P-wave $\chi_{bJ}(1P)$ states, collectively referred to as $\chi_b(1P)$ throughout the paper. The $\chi_b(1P)$ mesons are reconstructed through the radiative decay $\chi_b(1P) \to \Upsilon(1S)\gamma$ in the $\Upsilon(1S)$ rapidity and transverse momentum range $2.0 < y^{\Upsilon(1S)} < 4.5$ and $6 < p_{\mathrm{T}}^{\Upsilon(1S)} < 15\,\mathrm{GeV}/c$. The χ_{b2} and χ_{b1} states differ in mass by $20\,\mathrm{MeV}/c^2$ and the χ_{b1} and χ_{b0} states by $33\,\mathrm{MeV}/c^2$ [14]. Since these differences are comparable with the experimental resolution, the total fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays is reported. The results presented here use a data sample collected at the LHC with the LHCb detector at a centre-of-mass energy of $7\,\mathrm{TeV}$ and correspond to an integrated luminosity of $32\,\mathrm{pb}^{-1}$.

2   LHCb detector

The LHCb detector [15] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about $4\,\mathrm{Tm}$, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at $5\,\mathrm{GeV}/c$ to 0.6% at $100\,\mathrm{GeV}/c$, and an impact parameter resolution of $20\,\mu\mathrm{m}$ for tracks with high transverse momentum (p_{T}). Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The trigger consists of a hardware stage followed by a software stage which applies a full event reconstruction. The trigger used for this analysis selects a pair of oppositely-charged muon candidates, where either one of the muons has a $p_{\mathrm{T}} > 1.8\,\mathrm{GeV}/c$ or one of

the pair has a $p_T > 0.56\,\mathrm{GeV}/c$ and the other has a $p_T > 0.48\,\mathrm{GeV}/c$. The invariant mass of the pair is required to be greater than $2.9\,\mathrm{GeV}/c^2$. The photons are not used in the trigger decision.

For the simulation, pp collisions are generated using PYTHIA 6.4 [16] with a specific LHCb configuration [17]. Decays of hadronic particles are described by EVTGEN [18] in which final state radiation is generated using PHOTOS [19]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [20] as described in Ref. [21]. The simulated signal events contain at least one $\Upsilon(1S) \to \mu^+\mu^-$ decay with both muons in the LHCb acceptance. In this sample of simulated events the fraction of $\Upsilon(1S)$ mesons produced in $\chi_b(1P)$ decays is 47% and both the $\chi_b(1P)$ and $\Upsilon(1S)$ mesons are produced unpolarized.

3 Event selection

The reconstruction of the $\chi_b(1P)$ meson proceeds via the identification of an $\Upsilon(1S)$ meson combined with a reconstructed photon. The $\Upsilon(nS)$ candidates are formed from a pair of oppositely-charged tracks that are identified as muons. Each track is required to have a good track fit quality. The two muons are required to originate from a common vertex with a distance to the primary vertex less than $1\,\mathrm{mm}$.
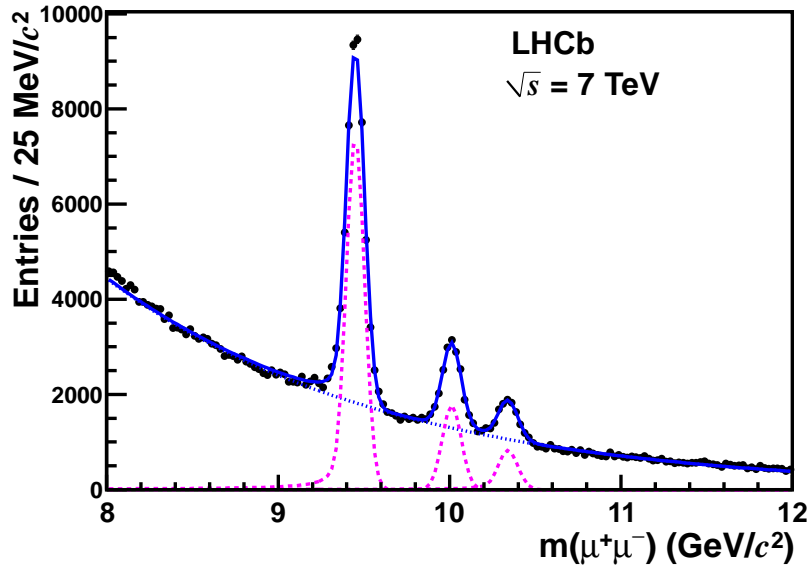

Figure 1: Distribution of the $\mu^+\mu^-$ mass for selected $\Upsilon(nS)$ candidates (black points), together with the result of the fit (solid blue curve), including the background (dotted blue curve) and the signal (dashed magenta curve) contributions.

The invariant mass distribution of the $\mu^+\mu^-$ candidates is shown in Fig. 1. It is

2

modelled with the sum of three Crystal Ball functions [22], describing the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ signals, and an exponential function for the combinatorial background. The parameters of the Crystal Ball functions that describe the radiative tail of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mass distributions are fixed to the values $a = 2$ and $n = 1$ [5]. The measured $\Upsilon(1S)$ signal yield, mass and width are $N_{\Upsilon(1S)} = 39\,635 \pm 252$, $m_{\Upsilon(1S)} = 9449.2 \pm 0.4\,\mathrm{MeV}/c^2$ and $\sigma_{\Upsilon(1S)} = 51.7 \pm 0.4\,\mathrm{MeV}/c^2$, where the uncertainties are statistical only.

The $\Upsilon(1S)$ candidates with a $p_\mathrm{T}^{\Upsilon(1S)} > 6\,\mathrm{GeV}/c$ and a $\mu^+\mu^-$ invariant mass in the range $9.36 - 9.56\,\mathrm{GeV}/c^2$ are combined with photons to form $\chi_b(1P)$ candidates. The photons are required to have $p_\mathrm{T}^\gamma > 0.6\,\mathrm{GeV}/c$ and $\cos\theta_\gamma^* > 0$, where θ_γ^* is the angle of the photon direction in the centre-of-mass frame of the $\mu^+\mu^-\gamma$ system with respect to the momentum of this system in the laboratory frame.

The $\chi_b(1P)$ signal peak observed in the distribution of the mass difference, $x = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$, is shown in Fig. 2 for the range $6 < p_\mathrm{T}^{\Upsilon(1S)} < 15\,\mathrm{GeV}/c$. It is modelled with an empirical function given by

$$\frac{dN}{dx} = A_1 \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\Delta M)^2}{2\sigma^2}} + A_2 (x - x_0)^\alpha e^{-(c_1 x + c_2 x^2 + c_3 x^3)}, \tag{1}$$

where A_1, ΔM, σ, A_2, x_0, α, c_1, c_2 and c_3 are free parameters. The Gaussian function describes the signal and the second term models the background. The number of $\chi_b(1P)$ signal decays obtained from the fit is 201 ± 55. The mean value of the Gaussian function is $447 \pm 4\,\mathrm{MeV}/c^2$ and its width is $19.0 \pm 4.2\,\mathrm{MeV}/c^2$. The expected values of the mass differences for the three $\chi_{bJ}(1P)$ states are $\Delta M(\chi_{b2}) = 452\,\mathrm{MeV}/c^2$, $\Delta M(\chi_{b1}) = 432\,\mathrm{MeV}/c^2$ and $\Delta M(\chi_{b0}) = 399\,\mathrm{MeV}/c^2$ [14]. The peak position in the data lies between $\Delta M(\chi_{b2})$ and $\Delta M(\chi_{b0})$ as expected for any mixture of $\chi_{bJ}(1P)$ states.

4 Fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays

The fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays is determined using the following assumptions. Firstly, all $\Upsilon(1S)$ originating from $\chi_b(1P)$ arise from the radiative decay $\chi_b(1P) \to \Upsilon(1S)\gamma$. Secondly, the total efficiency for $\Upsilon(1S) \to \mu^+\mu^-$ as a function of $p_\mathrm{T}^{\Upsilon(1S)}$ is the same for directly produced $\Upsilon(1S)$ and for those from feed-down from $\chi_b(1P)$. The total efficiency includes trigger, detection, reconstruction and selection. Thirdly, the photon detection, reconstruction and selection are independent of the $\Upsilon(1S) \to \mu^+\mu^-$. Hence the total efficiency for $\chi_b(1P)$ is factorized as $\epsilon_\mathrm{tot}(\chi_b) = \epsilon_\mathrm{cond}(\chi_b) \cdot \epsilon_\mathrm{tot}(\Upsilon)$, where $\epsilon_\mathrm{tot}(\Upsilon)$ is the total efficiency for $\Upsilon(1S)$ and $\epsilon_\mathrm{cond}(\chi_b)$ is the conditional efficiency for $\chi_b(1P)$ reconstruction and selection after the $\Upsilon(1S) \to \mu^+\mu^-$ candidate has been selected.

The second assumption is tested by comparing the $\Upsilon(1S)$ efficiencies obtained using simulated events for direct $\Upsilon(1S)$ and for $\Upsilon(1S)$ coming from decays of $\chi_b(1P)$ states. These efficiencies for each $p_\mathrm{T}^{\Upsilon(1S)}$ interval agree within the statistical error, which is less than 0.5%.

The conditional $\chi_b(1P)$ reconstruction and selection efficiency is estimated from simulation as
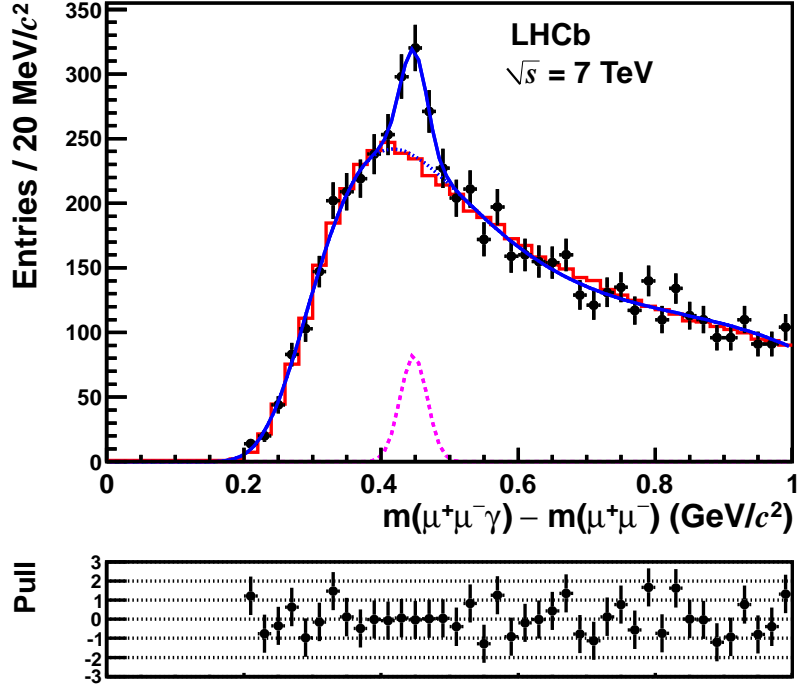
Figure 2: Distribution of the mass difference $m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ for selected $\chi_b(1P)$ candidates (black points), together with the result of the fit (solid blue curve), including background (dotted blue curve) and signal (dashed magenta curve) contributions. The solid (red) histogram is an alternative background estimation using simulated events containing a $\Upsilon(1S)$ that does not originate from a $\chi_b(1P)$ decay, normalized to the data. It is used for evaluation of the systematic uncertainty due to the choice of fitting model. The bottom insert shows the pull distribution of the fit. The pull is defined as the difference between the data and fit value divided by the data error.

$$\epsilon_{\rm cond}(\chi_b) = \frac{\epsilon_{\rm tot}(\chi_b)}{\epsilon_{\rm tot}(\Upsilon)} = \frac{N_{\rm rec}^{\rm MC}(\chi_b)}{N_{\rm gen}^{\rm MC}(\chi_b)} \cdot \frac{N_{\rm gen}^{\rm MC}(\Upsilon)}{N_{\rm rec}^{\rm MC}(\Upsilon)}, \tag{2}$$

where $N_{\rm rec}^{\rm MC}(\chi_b)$ and $N_{\rm rec}^{\rm MC}(\Upsilon)$ are the number of $\chi_b(1P)$ and $\Upsilon(1S)$ mesons obtained from the fit, and $N_{\rm gen}^{\rm MC}(\chi_b)$ and $N_{\rm gen}^{\rm MC}(\Upsilon)$ are the number of generated $\chi_b(1P)$ and $\Upsilon(1S)$ mesons, respectively. The value obtained is $\epsilon_{\rm cond}(\chi_b) = (9.4 \pm 0.1)\%$ for $6 < p_{\rm T}^{\Upsilon(1S)} < 15\,{\rm GeV}/c$ and $2.0 < y^{\Upsilon(1S)} < 4.5$.

The fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays is determined from the ratio

$$\frac{N_{\rm prod}(\chi_b)}{N_{\rm prod}(\Upsilon)} = \frac{N_{\rm rec}(\chi_b)/\epsilon_{\rm tot}(\chi_b)}{N_{\rm rec}(\Upsilon)/\epsilon_{\rm tot}(\Upsilon)} = \frac{N_{\rm rec}(\chi_b)/\epsilon_{\rm cond}(\chi_b)}{N_{\rm rec}(\Upsilon)}, \tag{3}$$

where $N_{\rm prod}(\chi_b)$ and $N_{\rm prod}(\Upsilon)$ are the total numbers of $\chi_b(1P) \to \Upsilon(1S)\gamma$ and $\Upsilon(1S)$ mesons produced, and $N_{\rm rec}(\chi_b)$ and $N_{\rm rec}(\Upsilon)$ are the numbers of reconstructed $\chi_b(1P)$ and

Table 1: Number of reconstructed $\chi_b(1P)$ and $\Upsilon(1S)$ signal candidates, conditional efficiency and fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays for different $p_\mathrm{T}^{\Upsilon(1S)}$ bins. The uncertainties are statistical only.

$p_\mathrm{T}^{\Upsilon(1S)}(\,\mathrm{GeV}/c)$	$6-7$	$7-8$	$8-10$	$10-15$	$6-15$
$N_\mathrm{rec}(\chi_b)$	41 ± 39	35 ± 22	91 ± 30	82 ± 29	201 ± 55
$N_\mathrm{rec}(\Upsilon)$	2730 ± 64	2193 ± 57	2866 ± 64	2627 ± 59	$10\,345 \pm 123$
$\epsilon_\mathrm{cond}(\chi_b)$ in %	6.7 ± 0.2	8.3 ± 0.2	10.0 ± 0.2	12.8 ± 0.2	9.4 ± 0.1
Fraction in %	23 ± 22	20 ± 12	32 ± 10	25 ± 9	21 ± 6

$\Upsilon(1S)$ mesons obtained from the fits to the data, respectively. As the muons from the $\Upsilon(1S)$ are explicitly required to trigger the event, the efficiency of the trigger cancels in this ratio. The fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays for $6 < p_\mathrm{T}^{\Upsilon(1S)} < 15\,\mathrm{GeV}/c$ and $2.0 < y^{\Upsilon(1S)} < 4.5$ is found to be $(20.7 \pm 5.7)\%$, where the uncertainty is statistical only.

The procedure is repeated in four bins of $p_\mathrm{T}^{\Upsilon(1S)}$, giving the results shown in Table 1 and Fig. 3. No significant $p_\mathrm{T}^{\Upsilon(1S)}$ dependence is observed. The mean of the measurements performed in the individual bins is consistent with the measurement obtained in the whole $p_\mathrm{T}^{\Upsilon(1S)}$ range.

5 Systematic uncertainties

Studies of quarkonium decays to two muons [3–5, 9, 10] show that the total efficiency depends on the polarization of the vector meson. The effect of the polarization has been studied by repeating the estimation of the efficiencies $\epsilon_\mathrm{tot}(\chi_b)$ and $\epsilon_\mathrm{tot}(\Upsilon)$ for the extreme $\chi_b(1P)$ and $\Upsilon(1S)$ polarization scenarios and taking the difference in $\epsilon_\mathrm{cond}(\chi_b)$ as the systematic uncertainty. The largest variation is found for the cases of 100% transverse and longitudinal polarization of the $\Upsilon(1S)$. We assign this relative variation of $^{+13}_{-26}\%$ as the range due to the unknown polarizations.

The systematic effect due to the unknown $\chi_{bJ}(1P)$, $J = 0, 1, 2$ relative contributions is estimated by varying these fractions in the simulation in such a way that the peak position of the mixture is equal to the peak position observed in the data plus or minus its statistical uncertainty. The maximal relative variation of the result is found to be 7%. This value is taken as a systematic uncertainty due to the unknown $\chi_{bJ}(1P)$ mixture.

The systematic uncertainty due to the photon reconstruction efficiency is determined by comparing the relative yields of the reconstructed $B^+ \rightarrow J/\psi (K^{*+} \rightarrow K^+\pi^0)$ and $B^+ \rightarrow J/\psi K^+$ decays in data and simulated events. It is assumed that the reconstruction efficiencies of the two photons from the π^0 are uncorrelated. The uncertainty on the photon reconstruction efficiency is studied as a function of p_T^γ. The largest systematic uncertainty is found to be 6% for photons in the range $0.6 < p_\mathrm{T}^\gamma < 0.7\,\mathrm{GeV}/c$, and is dominated by the uncertainties of the B^+ branching fractions.

Table 2: Relative systematic uncertainties on the fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays.

Source	Uncertainty (%)
Unknown $\chi_{bJ}(1P)$ mixture	7
Photon reconstruction efficiency	6
Signal and background description	5
Quadratic sum of the above	10

The systematic uncertainty due to the choice of the background fit model is estimated from simulated events containing an $\Upsilon(1S)$ that does not originate from the decay of a $\chi_b(1P)$. The distribution of the mass difference obtained with these events, using the same reconstruction and selection as for data, is shown in Fig. 2, normalized to the data below $0.38\,\mathrm{GeV}/c^2$. It describes rather well the background contribution above $0.38\,\mathrm{GeV}/c^2$, both in shape and level. The difference between the number of data events and the normalized number of simulated background events in the range $0.38 - 0.50\,\mathrm{GeV}/c^2$ gives an estimate of the signal yield. For $6 < p_\mathrm{T}^{\Upsilon(1S)} < 15\,\mathrm{GeV}/c$ the signal yield obtained using this method is 211 to be compared with 201 ± 55 obtained from the fit. The procedure is repeated in each $p_\mathrm{T}^{\Upsilon(1S)}$ bin. We also study the variation of signal yield by changing the normalization range to $0.0 - 0.3\,\mathrm{GeV}/c^2$ or $0.7 - 1.0\,\mathrm{GeV}/c^2$. The maximal relative difference of 5% is taken as the uncertainty due to the choice of the signal and background description. Systematic uncertainties are summarized in Table 2.

6 Results and conclusions

The production of $\chi_b(1P)$ mesons is observed using data corresponding to an integrated luminosity of $32\,\mathrm{pb}^{-1}$ collected with the LHCb detector in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. The fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays in the kinematic range $6 < p_\mathrm{T}^{\Upsilon(1S)} < 15\,\mathrm{GeV}/c$ and $2.0 < y^{\Upsilon(1S)} < 4.5$ is measured to be

$$(20.7 \pm 5.7 \pm 2.1^{+2.7}_{-5.4})\%,$$

where the first uncertainty is statistical, the second is systematic and the last gives the range of the result due to the unknown polarization of $\Upsilon(1S)$ and $\chi_b(1P)$ mesons.

This result can be compared with the CDF measurement of $(27.1 \pm 6.9 \pm 4.4)\%$ [11], obtained in $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$ in the kinematic range $p_\mathrm{T}^{\Upsilon(1S)} > 8\,\mathrm{GeV}/c$ and $|\eta^{\Upsilon(1S)}| < 0.7$.

The $\chi_b(1P)$ decays are observed to be a significant source of $\Upsilon(1S)$ mesons in pp collisions. This will need to be taken into account in the interpretation of the measured $\Upsilon(1S)$ production cross-section and polarization.
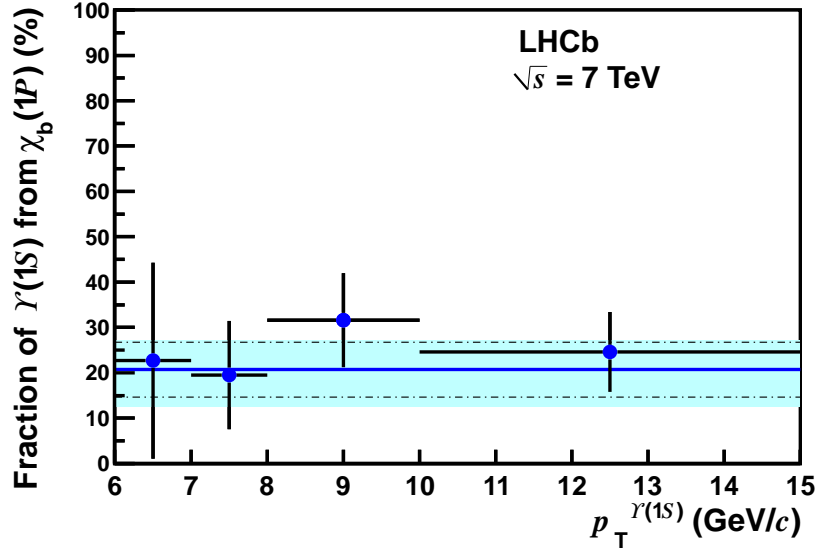
Figure 3: Fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays for different $p_{\mathrm{T}}^{\Upsilon(1S)}$ bins, assuming production of unpolarized $\Upsilon(1S)$ and $\chi_b(1P)$ mesons, shown with solid circles. The vertical error bars are statistical only. The result determined for the range $6 < p_{\mathrm{T}} < 15\,\mathrm{GeV}/c$ is shown with the horizontal solid line, its statistical uncertainty with the dash-dotted lines, and its total uncertainty (statistical and systematic, including that due to the unknown polarization) with the shaded (light blue) band.

Acknowledgements

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